LIGHTWAVES

Dielectric Materials and Devices

Project Leader: Norman A. Sanford

Staff: 4.3 Professionals, 1.0 Contractor

Funding level: $1.0 M

Funding sources: NIST (79%), Other Government Agencies (9%), Other (12%)

Objective: Develop advanced measurement methods for dielectric waveguide materials and processing procedures for these materials; interact with industry for the test and evaluation of advanced laser glasses and nonlinear optical materials; fabricate prototype devices from these materials.

Background: NIST's work in the characterization of dielectric materials, with emphasis on supporting new industrial developments in the field of integrated and guided-wave optics, began in 1988. The work has focused on rare-earth-doped laser glasses and ferroelectric ceramics such as lithium niobate and lithium tantalate. These materials are important since they are the backbone of new commercial directions of integrated optical technology. For example, compact solid-state glass waveguide lasers are viewed as important components for remote sensing and ranging technologies. NIST has worked closely with industrial collaborators, involving both materials development and device development, to help further this technology. Additionally, NIST has worked on the characterization of lithium niobate and lithium tantalate. These materials are used extensively in optical communication systems for modulators and switches. Components fabricated from these materials also find widespread use in optical guidance and control systems. Furthermore, lithium niobate waveguide devices are key elements used in compact blue/green lasers, which are in demand for data storage and reproduction graphic technologies.

Current Tasks:

1. Rare-earth-doped solid state laser and amplifier metrology

FY 1990	First reported neodymium-doped waveguide laser for continuous operation fabricated by ion-exchange in glass.
FY 1991	Mode-locking, Q-switching and tuning reported in waveguide lasers; first reported Y-branch waveguide laser and amplifier.
FY 1992	Dispersion of optical fiber amplifiers and rare-earth-doped waveguide amplifiers measured by low-coherence interferometry; first reported linewidth-narrowed, coupled-cavity waveguide laser fabricated; first reported neodymium-diffused lithium tantalate waveguide laser fabricated.
FY 1993	High efficiency, phosphate glass waveguide laser demonstrated and characterized.

FY 1994	Waveguide grating fabrication procedures established; waveguide lasers with distributed Bragg reflectors developed and characterized; passively Q-switched waveguide lasers demonstrated and analyzed.
FY 1995	Phosphate glass waveguide fabrication space investigated; numerical modeling study of continuous and pulsed erbium-doped waveguide lasers initiated.
FY 1996	Characterized near-field intensity profiles, effective indices and diffusion profiles of rare-earth-doped waveguides; Modelled continuous and Q-switched operation of waveguide lasers; Demonstrated first reported erbium-diffused and neodymium-diffused lithium niobate waveguide lasers (with titanium-diffused guides) that were stable under optical pumping at 980 nanometers and 800 nanometers, respectively.
FY 1997	Study optimization of glass composition and laser design; Demonstrate Q-switched lithium niobate waveguide lasers operating near 1550 nanometers; Demonstrate distributed feedback waveguide lasers operating near 1550 nanometers; Explore feasibility of stable lithium niobate waveguide laser operating near 1083 nanometers; Explore feasibility of grafting semiconductor saturable absorbers on glass waveguide lasers; Continue to optimize glass erbium/ytterbium composition and fabrication of lasers; Measure erbium/ytterbium energy transfer.
FY 1998	Demonstrate mode-locked waveguide lasers operating near 1550 nanometers; demonstrate arrays of distributed-feedback lasers with deliberate spacing in output wavelength; demonstrate grafted semiconductor saturable absorber on glass waveguide lasers for mode-locking and Q-switching; continue to spectroscopically investigate cross-section, energy transfer, and upconversion in order to optimize glass composition and fabrication of lasers.

2. Metrology of nonlinear optical materials

FY 1989	Characterized photorefractive instabilities from two-wave coupling in lithium niobate waveguides formed by proton exchange.
FY 1994	Maker-fringe system constructed to map wafer uniformity for waveguide devices; theoretical model of reflected and transmitted Maker-fringe signatures established for various sample orientations and pump and signal polarizations; studies of domain-inverted segments in lithium niobate waveguides initiated.
FY 1995	Nonuniformities in index (and hence composition) mapped over 50-millimeter and 76-diameter lithium niobate wafers by Maker fringe analysis; thickness uniformity of lithium niobate wafers also mapped; initial correlations with x-ray topographs performed; Maker-fringe analysis used to help characterize thin lithium niobate films produced by industrial collaborators; cross-section and shape of domain-reversed segments in lithium niobate waveguides studied
FY 1996	Mapped 100-millimeter diameter lithium niobate wafers by Maker fringe analysis and corroborated lithium diffusion gradient; Studied apparent stress artifacts in wafers and correlated effect with device yield data from collaborator; Obtained initial results using two non-axial pumping beams for Maker fringe analysis; Constructed apparatus for the high-voltage poling of domain-engineered lithium niobate and lithium tantalate.
FY 1997	Establish measurement techniques for domain-engineered segments which utilize both nonlinear optical methods and electric-force microscopy; Study parameter space for the optimization of forward versus transverse domain growth; Establish transmission-electron microscopy study of domain-engineered structures; Fabricate domain-engineered components for

wavelength synthesis in Time and Frequency Division applications; Establish nonlinear optical methods, collaborating with crystal growers, to separate surface from bulk effects in lithium niobate and related materials using single and double-beam probes; Begin study of nonlinear optical characterization of glass interfaces.

FY 1998 Map uniformity of glass layers via interfacial sum-frequency generation; Measure uniformity and microscopic features of domain formation and growth using optical and microanalytical tools; Collaborate with crystal growers to improve material for high-yield domain engineering.

Semiconductor Materials and Devices

Project Leader:	David H. Christensen
Staff:	3.7 Professionals, 2.3 Postdocs, 2.0 Guest Researcher
Funding level:	$1.1 M
Funding sources:	NIST (95%), Other Government Agencies (5%)
Objective:	Develop measurement methods and provide measurements to support the efficient manufacture of semiconductor optoelectronic devices; provide custom devices to support research in NIST, other Government laboratories, and industry.

Background: This project was established in 1994 and has earlier foundations in efforts dating to 1990-91 when NIST researchers contributed to metrology for the precision manufacturing of semiconductor epitaxial multilayers. The particular impact was in assisting the development of the first commercially available vertical-cavity surface-emitting lasers. The project has extended the *ex-situ* measurements to *in-situ* monitoring during epitaxial growth, with the goal of advancing controlled-precision optoelectronic device manufacturing. In the field of optoelectronic interconnects, project researchers collaborate with industry and other Division researchers to develop measurements which support the manufacture and specification requirements for lasers used in interconnect systems. Efforts are underway to develop expertise which supports the group III-nitride industry, which is developing materials and devices for the blue/ultraviolet region.

Current Tasks:

1. *In-situ* optical metrology and process control of epilayer manufacturing

FY 1994	Atomic absorption spectroscopy (AAS) system installed on semiconductor growth chamber; Aluminum gallium arsenide layer growth monitored; Growth of Bragg reflectors measured by *in-situ* optical reflectance spectroscopy (ORS); Calibrated atomic absorption measurement to *in situ* measurements of epilayers; Installed shallow-angle ultraviolet reflectance (UVR) monitor; Measured growth of quantum wells in real-time.
FY 1997	Investigate closed loop control of epilayer growth; Investigate manufacture of test structures and/or reference standards for evaluation and optimization of growth stability; Correlate *in situ* monitored structures to *ex situ* measurements to advance controlled-precision manufacturing; Increase operational state of crystal growth system to include source materials of indium, beryllium, silicon, phosphorus and arsenic (As_2); Publish and report results of AAS/UVR and ORS monitors.
FY 1998	Develop *in situ* optical monitoring of indium aluminum gallium phosphide materials in support of visible optoelectronics component industry.

2. *Ex-situ* characterization of semiconductor growth and processing

FY 1991 Vertical-cavity surface-emitting laser (VCSEL) structures characterized by x-ray, electron-beam, and optical metrologies, and by measurement simulations; High degree of correlation among measurement methods shown for layer thicknesses, uniformity, and composition; Assisted industry in development of first commercially available VCSELs.

FY 1992 Distributed feedback VCSELs with distributed quantum wells fabricated and characterized; Impact of correlated characterization verified by demonstrating the narrowest linewidth distributed feedback VCSEL and efficient optically-pumped VCSELs.

FY 1993 Dielectric function of individual quantum wells measured from distributed reflectance spectroscopy, and theoretical model for gallium arsenide quantum wells confirmed; Cross-sectional micro-photoluminescence technique developed to distinguish features of buried semiconductor layers; Correlation between cross-sectional and surface-normal emission measurements established.

FY 1994 Spatio-temporal evolution of vacancy-assisted aluminum-gallium interdiffusion in quantum well heterostructures quantified by cross-sectional micro-photoluminescence, new theoretical model confirmed, impact on semiconductor device manufacturing demonstrated; Test structures for evaluation and optimization of epilayer uniformity developed.

FY 1995 Period deviations in distributed Bragg reflectors measured by reflectance spectroscopy and modeled; Parameter space of interdiffusion-during-annealing studies extended to include matrix of arsenic overpressure and temperature.

FY 1996 Measured and modeled influence of effusion-cell temperature drift during distributed Bragg reflector manufacturing; Correlated high-resolution x-ray diffractometry measurements to reflectance spectroscopy and electron microscopy measurements of systematic and random period deviations in multilayers.

FY 1997 Advance precision *ex-situ* metrology of semiconductor test structures and/or measurement standards for evaluating and optimizing 3-D epitaxial uniformity; Correlate *in-situ* monitored structures to *ex-situ* measurements to advance controlled-precision manufacturing; Report results on correlation studies; investigate influence of manufacturing variations on devices used in optical interconnect industry.

FY 1998 Develop atomic force and scanning near-field microscopic measurements for nanoscale optoelectronic structure characterization; Develop manufacturing and metrology of quantum-dot materials and devices.

3. Semiconductor material and device metrology for advanced applications

FY 1993 Completed study of optoelectronic technology and metrology required to enhance computing; Program established to address the measurement needs of the VCSEL industry and applications of optoelectronic interconnects.

FY 1994 Metrology needs of the VCSEL industry assessed and complementary Division resources identified; Program begun to assist industry with measurements and standards for VCSELs and their applications in fiber-based data interconnects.

FY 1995 VCSEL devices obtained from industry, and packaging for dc-biased and high-speed testing established; Measurement stations and methods for measuring large-signal return-to-zero modulation bandwidth, turn-on jitter, near and far-field beam profile, and relative intensity noise established (joint with 815.01).

FY 1996 Studied VCSEL measurands as function of environmental and drive parameters; Performed data interpretation and modeling of VCSEL emission properties; Determined measurement problems and technological barriers of group III-nitride technology; Collaborated with NIST researchers on joint proposal for nitride measurements support to industry.

FY 1997 Establish ultrafast mode-locked laser, homodyne detection, and fully integrated measurement system for device and material characterization; Investigate spectral mode content of VCSEL devices for optical interconnects and influence of native-oxide manufacturing technology; Explore expertise development which supports the group III-nitride industry.

FY 1998 Investigate ultrafast carrier and photon dynamics of VCSELs at the femtosecond time-scale.

4. Devices for advanced metrology

FY 1994 Concept of environment (e.g., temperature, electromagnetic field) sensor using microcavity devices such as VCSELs, resonant-cavity light emitting diodes, and Fabry-Perot filters formulated; NASA support secured.

FY 1995 Simultaneous electrical and optical biased measurement station established; Light-current-voltage, photocurrent spectra, and threshold conditions measured with mixed electro-optical addressing; Power-by-light operation demonstrated on fully-packaged and non-contacted devices; Industry, in-house, and university-supplied VCSELs tested.

FY 1996 Designed custom device which stabilized optical-pump coupling but maintained laser sensitivity to environment; Fabricated and tested prototype device; Established and characterized fiber-interfaced optical power and sensing.

FY 1997 Advance methods of photonic/electronic band engineering into ultrafast device metrology; Develop saturable Bragg reflectors for metrology systems used in other projects in the division; Investigate impact of optoelectronic band engineering on interconnect and detector industries; Calibrate and incorporate dopant sources into device structures.

FY 1998 Advance saturable Bragg reflectors into In- and P-containing compounds.

Fiber and Discrete Components

Project Leader: Sarah L. Gilbert

Staff: 1.8 Professionals, 1.0 Postdoc, 2.0 Contractors

Funding level: $0.46 M

Funding sources: NIST (100%)

Objective: Develop measurement methods for characterization of optical fiber components and discrete components and develop standards needed by industry for these components.

Background: This project is concerned with the characterization of optical components and development of standards needed to calibrate commercial instruments which measure component properties. Wavelength standards are needed to calibrate instruments which measure the wavelengths of sources and characterize the wavelength dependence of components in wavelength division multiplexing optical fiber communication systems. Future optical communication systems will likely incorporate recently developed components, including many promising devices such as fiber lasers, dispersion compensators, and band pass filters containing Bragg fiber gratings. There is a need for standards and characterization of these components in order to both evaluate their reliability and ensure that the system specifications can be met. Polarization dependence such as polarization-dependent loss and polarization-dependent gain in components can affect a system's performance, especially when there are many components in the system. Presently, there are commercial instruments for measuring polarization-dependent loss, but no calibration standards exist for these instruments.

Current Tasks:

1. Wavelength standards for optical communications

FY 1990 Designed and constructed a single-longitudinal mode erbium-doped fiber laser and characterized its frequency noise.

FY 1991 Conducted spectroscopy of acetylene using the fiber laser to assess potential use for a wavelength standard; Developed a light emitting diode and absorption cell based moderate-accuracy wavelength standard.

FY 1992 Conducted high-resolution laser spectroscopy of rubidium to assess potential use for a high-accuracy wavelength standard in the 1500 nanometer region; Constructed moderate-accuracy wavelength standard for the Air Force.

FY 1993 Stabilized the fiber laser to a narrow absorption line of laser-cooled rubidium, demonstrating the system's potential as a high-accuracy wavelength standard; Conducted a detailed study of the line shapes observed in this system.

FY 1994 Constructed a new rubidium vapor cell trap for the high accuracy wavelength standard in the 1500 nanometer region; Began investigating the use of hydrogen iodide and hydrogen cyanide as wavelength references in this region

	for moderate-accuracy wavelength standards; Developed plan for meeting NIST traceability need for wavelength calibration at optical communication wavelengths via absorption cells to be distributed as standard reference material (SRM).
FY 1995	Built and tested hydrogen cyanide ($H^{13}CN$) vapor cells for moderate-accuracy wavelength references; Supplied two companies with absorption cells to evaluate whether absorption cell SRMs will meet their calibration needs.
FY 1996	Developed acetylene absorption cell standard reference material; Measured the pressure-induced shift of acetylene absorption lines; Supplied three companies with fiber-pigtailed absorption cells.
FY 1997	Provide acetylene absorption cell SRM; Develop and provide hydrogen cyanide absorption cell SRM; Transfer absorption cell technology to a company.
FY 1998	Provide absorption cell SRM units as needed; Evaluate reproducibility of high-accuracy wavelength standard based on laser spectroscopy of rubidium.

2. Metrology for photo-induced Bragg gratings in optical fiber

FY 1992	Developed the capability to write Bragg reflection gratings in optical fiber.
FY 1993	Characterized fiber grating growth dependence on time and the intensity of the ultraviolet (UV) light, compared results with theoretical models.
FY 1994	Investigated the correlation of fiber grating growth and blue fluorescence emitted during exposure to ultraviolet light; Constructed a single-longitudinal mode fiber laser incorporating fiber gratings.
FY 1995	Evaluated the thermal stability of fiber Bragg gratings written in hydrogen-loaded and unloaded optical fiber using either pulsed or continuous-wave light; Characterized the intensity and frequency noise of fiber lasers containing fiber gratings.
FY 1997	Characterize fiber grating-stabilized diode lasers; Investigate measurement techniques to characterize bulk glass UV photosensitivity.
FY 1998	Study UV photosensitivity of bulk glass; Investigate stability of fiber gratings under illumination of intense laser light.

3. Polarization-dependent loss and gain metrology

FY 1994	Developed plan for constructing a polarization-dependent loss (PDL) measurement system.
FY 1995	Assessed industry need for PDL standards; Developed two PDL measurement systems.
FY 1996	Completed characterization of PDL measurement systems; Characterized short-term stability PDL artifact reference.
FY 1997	Document PDL measurement system; Study PDL of fiber connectors and selected WDM fiber components; Characterize long-term stability of PDL artifact reference; develop polarization-dependent gain measurement capability and begin measurements on a fiber amplifier.
FY 1998	Develop PDL Standard Reference Material; study polarization-dependent gain of fiber amplifiers.

4. Mode-Isolation Metrology for Polarization Maintaining Fiber

FY 1991	Began work on mode-isolation (h-parameter) measurement in high birefringence optical fiber at request of the Telecommunication Industries Association (TIA).
FY 1992	NIST/TIA interlaboratory comparison of mode-isolation measurements conducted.
FY 1994	Participated in drafting a mode-isolation TIA fiber optic test procedure.
FY 1996	Worked with TIA to evaluate a new mode-isolation measurement technique.
FY 1997	Conduct and participate in a mode-isolation measurement interlaboratory comparison involving new technique.

Integrated Optics Metrology

Project Leader: Matt Young

Staff: 1.5 Professionals, 0.7 Postdoc, 0.7 Contractor

Funding level: $0.4 M

Funding sources: NIST (100%)

Objective: Develop advanced measurement methods for integrated optical waveguides. Interact with standards groups to provide a metrology base for lightwave communications industry.

Background: As the optical fiber industry moves toward local area networks and toward fiber to the home, there is increasing need for inexpensive passive components such as splitters. Additionally, such components are needed because long-distance telephony is retrofitting to wavelength division multiplexing. Several companies are manufacturing 1 × N splitters or are about to market them. There are, however, no standard measurement procedures similar to those for fiber index profile and mode-field diameter, nor are there artifact standards similar to those for fiber geometry. Further, it is not obvious how to perform analogous measurements, for example, because the mode field pattern of an integrated optical waveguide is not circularly symmetric or because the fiber measurement is performed using a cutback technique or a mandrel wrap. Thus, several critical measurements need examination.

Current Tasks:

1. Develop metrology for integrated optical components

FY 1988	Developed a photo-thermal method for nondestructively measuring loss in channel waveguides.
FY 1994	Identified industry’s need for measurements on passive waveguides.
FY 1995	Developed low coherence reflectometer for probing integrated optical waveguides; Started preliminary collaborations with university and industrial laboratory on integrated optical metrology.
FY 1996	Continued development of low coherence reflectometer; Characterized Y-branch waveguides and measured dispersion of an optical waveguide and performed preliminary measurements on waveguides in various substrates; Began work on confocal microscopy of waveguide end faces for mode-field diameter measurements.
FY 1997	Measure loss in integrated optical waveguides using low coherence reflectometer; Measure mode-field diameter of waveguide.
FY 1998	Study coupling loss between waveguides and single-mode fibers.

Optical Fiber Sensors

Project Leader: Kent B. Rochford

Staff: 2.2 Professionals, 0.6 Technician, 1.0 Post Doc, 0.5 Guest Researcher

Funding level: \$0.6 M

Funding sources: NIST (70%), Other Government Agencies (29%), Other (1%)

Objective: Provide metrology to support the optical fiber sensor industry and develop advanced sensing technology for other government and industry laboratories. Provide polarization measurements and develop polarization standards for industry. Provide optical disc substrate measurements.

Background: This project is responding to the growing fiber-optic sensors industry by developing standards and calibrations where few exist, characterizing sensor materials, assisting in the characterization of components and sensing methods, and educating the measurement community to the advantages of optical fiber sensors. We provide the industry and other government agencies with traceability, measurement expertise, neutral evaluation of technologies, and pre-commercial development of advanced prototypes. We recently developed a Standard Reference Material for linear retardance and perform Special Tests for retardance. We are beginning an effort to calibrate optical disc retardance measurements and perform more general measurements on optical discs.

Current Tasks:

1. Advanced sensor systems, components, and materials research

FY 1985	First demonstration of fiber annealing to remove birefringence.
FY 1986	Demonstration of optical fiber current measurements to 70 megamperes.
FY 1987	Extended study of precision of electro-optic and magneto-optic sensors published.
FY 1988	Research on Faraday effect in ferromagnetic iron garnets begun.
FY 1989	High speed, high sensitivity (100pT/$\sqrt{\mathrm{Hz}}$ noise equivalent field) sensors based on the Faraday effect in yttrium-iron-garnet (YIG) demonstrated.
FY 1990	Annealing technology transferred to industry.
FY 1991	Published description of fiber annealing technology.
FY 1993	Demonstrated very-high-sensitivity magnetic field sensor (1.4pT/$\sqrt{\mathrm{Hz}}$ noise equivalent field) using flux concentrators; Measured radiation effects in iron garnets; Explained polarization effects in Sagnac current sensors.
FY 1994	Completed study of impediments to commercialization of fiber sensors for Navy shipboard applications; Tested iron garnet materials resulting from Small Business Innovative Research Program grant; Designed and constructed a high-speed, high-sensitivity current sensor; Demonstrated improved fiber annealing technique.

FY 1995	Developed and demonstrated laser-as-detector technique in optical fiber sensor systems; Completed self-calibrating temperature sensor system; Field-tested high-speed current sensor; Work on expanded core fiber for lensless coupling begun.
FY 1996	Thermally expanded an optical fiber core; Characterized and improved high-sensitivity magnetic field sensor system.
FY 1997	Incorporate novel garnets into magnetic field sensor system; Characterize thermally expanded core fiber; Begin work on low-coherence sensor systems.
FY 1998	Deliver miniaturized magnetic field sensor to sponsor; Demonstrate extended dynamic range low-coherence sensor; Develop diffraction-based sensors.

2. Basic metrology and standards development

FY 1988	Definitive study of birefringent linear retarder (waveplate) stability.
FY 1994	Tested prototype retardance standards and demonstrated very good performance for wavelength, temperature, and incident-angle dependencies; Identified long-term drift problem due to humidity.
FY 1995	Developed and confirmed a model for the standard retarder package performance; Redesigned package to minimize water vapor transmission; completed the lifetime testing of the standard retarder.
FY 1996	Measured the Verdet constant of optical fiber with improved accuracy for Los Alamos National Laboratory; Performed special tests on retarders; Completed uncertainty analysis of standard retarder and three supporting measurement methods; Completed interlaboratory comparison of retardance measurements with eight U.S. participants; Characterized devitrification of annealed fiber sensors.
FY 1997	Establish Standard Retarder as a Standard Reference Material (SRM) and provide measurement support.
FY 1998	Produce standard retarder for operation at 633 nanometer wavelength.

3. Optical data storage

FY 1995	Investigation of optical data storage industry needs begun; Participated in NIST planning workshop.
FY 1996	Identified and prioritized measurement needs of the compact disc replication industry; Investigated limits of atomic force microscopy for disc topology measurements.
FY 1997	Develop techniques for optical disc characterization; Conduct interlaboratory comparison of optical disc retardance; Develop techniques for measuring disc retardance at 780 and 650 nanometers.
FY 1998	Develop SRM for optical disc retardance; Characterize calibration artifacts for compact disc measurements.

4. Optical fiber sensor commercialization

FY 1991	Transferred optical fiber annealing technology to U.S. company.
FY 1994	Transferred the improved annealing technology to U.S. company.
FY 1995	Provided garnet and annealed fiber current sensors to a U.S. company for evaluation.
FY 1996	Transferred optical fiber annealing technology to a second U.S. company.

FY 1998 Identify U.S. companies interested in diffraction-based sensor technology or expanded fiber core technology.

Optical Fiber Metrology

Project Leader:	Douglas L. Franzen
Staff:	4.5 Professionals, 0.3 Technician
Funding level:	$0.9 M
Funding sources:	NIST (93%), Other Government Agencies (7%)
Objective:	Develop advanced measurement methods and Standard Reference Materials for optical fibers; interact with standards groups to provide a metrology base for the lightwave communication industry.

Background: During the 1980s, optical fibers were introduced into the nation's telecommunication system to carry large quantities of long distance information. As the technology matured, more fiber moved into metropolitan areas and local area networks. Local loops utilize many more connection points; therefore, dimensional tolerances are important and improvements are necessary for lower loss connectors. In addition, long distance link technology continues to improve. Bit rates are increasing and the advent of optical amplifiers allows for direct optical paths thousands of kilometers in length; this and other trends toward wavelength division multiplexing require improved measurements of fiber dispersion. Over the years, NIST's efforts have evolved along with the industry, focusing on a wide range of measurement problems as they became important, and assisting in their resolution. This has led to a close involvement with the Telecommunications Industry Association (TIA) and with international standards organizations. NIST has participated in the development of more than twenty TIA standards, often serving as a neutral party in their evaluation through interlaboratory comparisons. In recent years, the industry's need for standard reference materials (SRMs) has grown; NIST presently provides an SRM for fiber cladding diameter that is used to calibrate the draw towers for most of the fiber commercially manufactured in the United States, and is preparing several other SRMs.

Current Tasks:

1. Develop dimensional metrology for optical fiber

FY 1989	TIA asked NIST to develop cladding diameter SRM.
FY 1990	Contact micrometer developed with Manufacturing Engineering Laboratory, NIST.
FY 1991	Scanning confocal microscope developed; Limitations of video microscopy studied.
FY 1992	White light interference microscope developed; International round robin completed with the International Telegraph and Telephone Consultative Committee; SRM holder evaluated in TIA round robin.
FY 1993	Definitive publication on cladding diameter published in NIST Journal of Research; Cladding diameter SRM available for sale.

FY 1994	International round robin completed to evaluate SRM housings and calibrations; Completed TIA round robin on fiber coating geometry.
FY 1995	SRM for coating geometry developed; TIA round robin to evaluate ferrule and pin gages complete; NIST Tech Note written on geometry round robins.
FY 1996	SRMs for connector ferrule outside and inside diameter (pin gages) available for sale; Investigated optical interferometric measurement methods for connector protrusion/undercut.
FY 1997	Investigate mechanical/optical measurement methods based on near field probes for connector protrusion/undercut; Develop connector protrusion/undercut SRM; SRM for coating diameter available for sale; Develop reference near-field and far-field measurement systems for mode field diameter.
FY 1998	Connector protrusion/undercut SRM available for sale.

2. Develop dispersion metrology for optical fiber

FY 1993	Initiated development of frequency domain phase shift system for chromatic dispersion measurements.
FY 1994	Initiated development of measurement methods for polarization mode dispersion (PMD); Completed frequency domain phase shift system; Studied fiber configuration for chromatic dispersion SRM; Initiated PMD round robin with TIA members.
FY 1995	Completed evaluation of PMD methods; Completed PMD round robin; Initiated TIA round robin to evaluate chromatic dispersion reference fibers; Completed development of differential phase shift system to measure zero dispersion wavelength.
FY 1996	Documented performance of PMD SRM; Completed TIA chromatic dispersion round robin and documented chromatic dispersion SRM.
FY 1997	Chromatic dispersion SRM available for sale; PMD SRM available for sale.
FY 1998	Develop system to measure multimode fiber chromatic dispersion.

3. Develop metrology for nonlinear fiber properties

FY 1994	Identified key needs of industry and initiated NIST program.
FY 1995	Measured pulse response of Fabry-Perot filters and determined effect of non-linearities; Completed capability for measuring four-wave mixing effects.
FY 1996	Determined relation between four-wave mixing efficiency and zero dispersion wavelength - published results; Presented four-wave mixing work to TIA;
FY 1997	Determine whether four-wave mixing can predict chromatic dispersion length uniformity.
FY 1998	Conduct industry round robin on non-linear fiber properties.

4. Develop metrology for system/field measurements

FY 1992	Developed time domain methods for calibrating optical time-domain reflectometer (OTDR) group delay; Constructed moderate accuracy wavelength standard to calibrate optical spectrum analyzers; Investigated mode-locked fiber lasers as strobes for optical waveform sampling.
FY 1993	Developed interferometric low-coherence techniques for fiber length and group delay measurements.

FY 1994	Developed artifact calibration standards for group index of single and multimode optical fibers; Demonstrated efficient optical waveform sampling based on four-wave mixing effects; Initiated program to determine optimum launching conditions for multimode fibers in support of fiber computer bus interconnects (ATP funded); Developed high resolution OTDR for local area network applications.
FY 1995	Delivered group index OTDR calibration artifacts to Navy; Designed beam optics system for multimode fiber bandwidth measurements.
FY 1996	Evaluated and modified, with TIA, existing test procedures for multimode fiber bandwidth.
FY 1997	Complete multimode fiber bandwidth round robin with TIA members; Develop high resolution measurement method for differential mode delay in multimode fibers; Develop reference measurement system and SRM for multimode fiber bandwidth.
FY 1998	SRM for multimode fiber bandwidth available for sale.

5. Develop metrology for fiber amplifiers

FY 1994	Identified the key metrology issues for fiber amplifiers.
FY 1995	Collaborated with TIA and international standards groups to plan round robin for noise figure and spectral gain.
FY 1996	Initiated international round robin and obtained preliminary NIST measurements of noise.
FY 1997	Interact with the TIA to provide a NIST measurement capability to the industry.
FY 1998	Complete international round robin and issue report.

High Speed Source and Detector Measurements

Project Leader: Paul D. Hale

Staff: 4.5 Professionals, 1.0 Guest Researchers, 0.8 Technician, 1.0 Contractor

Funding level: $1.1 M

Funding sources: NIST (64%), Other Government Agencies (32%), Other (4%)

Objective: Provide advanced metrology, standards, and measurement services relating to temporal properties of optical sources and detectors used in association with optoelectronic systems.

Background: High bandwidth measurements are needed to support high-performance systems which take advantage of the potential bandwidth of optical fiber. Systems presently being installed operate at 5 to 10 gigabits per second using pure optical time division multiplexing (OTDM) and research is being done on the next generation of OTDM systems at 20 to 40 gigabits per second. Methods are needed to characterize the impulse and frequency response of high speed sources and detectors to at least the third harmonic of the system modulation rate. As new optoelectronic technologies have emerged, NIST has developed new laser and detector standards to support this growth. For example, the relatively recent development of vertical cavity surface emitting lasers (VCSELs) has shown the need for concurrent development of applicable measurement standards and techniques specific to this technology. Burst mode operation in asynchronous transfer mode (ATM) networks requires characterization at very low frequencies. Increasingly tight tolerances in both digital and analog systems require frequency response measurements with low uncertainty. Source and detector noise measurements are required to predict low bit error rates (BERs) in computer interconnects, high carrier to noise ratios (CNRs) in analog systems, and to support erbium-doped fiber amplifier (EDFA) noise figure (NF) measurements using electrical noise methods. Intensive use of laser target designators by the armed forces requires traceable low level pulse power and energy calibration standards at 1.06 and 1.55 micrometers.

Current Tasks:

1. Develop vertical cavity surface emitting lasers (VCSEL) measurement methods and standards

FY 1994	Recognized need for VCSEL measurements and successfully proposed program for funding.
FY 1995	Developed methods to quantitatively measure beam profile, impulse modulation response, turn-on jitter, and relative intensity noise (RIN) in vertical cavity surface emitting lasers.
FY 1996	Established RIN measurement system with controlled optical feedback; Interfaced an automated beam profile measurement system with RIN measurement system.

FY 1997	Correlate beam profile, RIN, drive current, and polarization, investigate mode partitioning, and determine effects of modulation; Investigate modulation effects in VCSELs and measure multimode fiber bandwidth.

2. Noise measurements and standards

FY 1994	Developed competence in RIN of diode lasers to determine limitations of existing measurement techniques.
FY 1995	Performed RIN measurements on edge-emitting lasers at room temperature and liquid nitrogen temperature (77 kelvin) over the frequency range between 1 to 10 gigahertz.
FY 1996	Documented industry needs for optoelectronic noise measurements; Began development of techniques and apparatus for measuring RIN which are suitable for supporting optical amplifier noise measurements and low level measurements on distributed feedback (DFB) lasers; Completed cryogenic measurements of RIN of various diode laser sources.
FY 1997-98	Continue development and characterization of RIN measurement techniques supporting optical amplifier noise measurements and measurement of low RIN (-160 dB/Hz) DFB lasers.

3. Develop impulse response measurement capability

FY 1993	A titanium-doped sapphire laser which produced very short pulses (100 fs) was completed; detectors and modulators with picosecond response evaluated.
FY 1994	Received calibration requests and, consequently, modified system to accommodate customers' detectors.
FY 1995	Performed two Special Test calibrations on optical power detectors.
FY 1996	Began development of a mode-locked chromium-doped yttrium aluminum garnet (Cr^{+4}:YAG) laser for generating short (100 fs) optical pulses at wavelengths of 1.55 micrometers or 1.3 micrometers, Began development of photoconductive methods for calibrating optoelectronic frequency response above 40 gigahertz; Investigated industry need for on-wafer and packaged device frequency response metrology.
FY 1997	Continue development of mode-locked Cr^{+4}:YAG laser, and development of photoconductive methods for calibrating optoelectronic response in both magnitude and phase.
FY 1998	Compare vector frequency response calculated using time domain method with heterodyne measurements.

4. Detector frequency response measurements

FY 1992	Received inquiries from industry for photodiode frequency response in the frequency range between 0.050 and 20 gigahertz; Investigated various measurement methods by literature search and talking to industry representatives; Acquired parts for heterodyne measurement system.
FY 1993	Constructed heterodyne measurement system operable over the frequency range between 0.05 and 30 gigahertz; Investigated candidates for transfer standards; Constructed 20 gigahertz transfer standard for Navy.
FY 1994	Extended heterodyne coverage up to 40 gigahertz and down to about 300 kilohertz; Participated in frequency response intercomparison with the

	National Physical Laboratory in Great Britain which demonstrated good agreement.
FY 1995	Developed method for transferring photoreceiver calibration; Extended range of heterodyne system to 50 gigahertz and down to 100 kilohertz; Calibrated over 20 detectors and transfer standards for industry.
FY 1996	Documented uncertainty analysis of frequency response measurements of a photoreceiver/power sensor transfer standard; Built and characterized synthesized modulation source for high-resolution measurements (between DC and 1 gigahertz); Continued comparison with the National Physical Laboratory in Great Britain. Calibrated 19 photodetectors and transfer standards for industry.
FY 1997	Complete documentation of photoreceiver/power sensor transfer standard calibration service; Implement changes in synthesized source to achieve acceptable operation at 100 kilohertz; Begin documentation of calibration service for "bare" photoreceivers; Continue comparison with the National Physical Laboratory in Great Britain and other standards laboratories; Investigate industry and military need for 800 nanometer or 1550 nanometer wavelength ranges and frequency coverage up to 110 gigahertz.
FY 1998	Continue comparisons with the National Physical Laboratory and other standards laboratories; Continue investigations of repeatability and age dependent effects in detectors; Extend measurement capability to 800 nanometers and/or 1550 nanometer wavelength ranges and extend measurement technology to higher frequency range up to 110 gigahertz for RF photonic applications.

5. Develop new pulsed laser measurement capability

FY 1992-93	Designed, constructed, and delivered two low-level radiometers for the Navy Metrology Center for measuring peak power of Q-switched pulses from laser target designator and range finder systems.
FY 1995	Delivered seven low level radiometers; began upgrade of low-level pulse measurements system to improve accuracy by a factor of two and reduce measurement time.
FY 1996	Continued low-level system upgrade including assessment of Type B uncertainties; Transferred technology for construction of six low-level radiometers to Navy; calibrated two of these radiometers.
FY 1997	Calibrate remaining four low-level Navy-constructed radiometers; Continue low-level system upgrade; Design prototype radiometer for 1.55 micrometer wavelength light; Construct low-level measurement system for 1.55 micrometer light; Deliver prototype radiometer to the Navy; Document needs of lidar and remote sensing industries for pulsed radiometric measurements.
FY 1998	Continue work on low-level radiometers for Navy; develop program in remote sensing.

Laser Radiometry

Project Leader: Chris Cromer

Staff: 6.5 Professionals, 3.0 Contractors, 1.2 Technicians, 1.0 Post Doc

Funding level: $1.4 M

Funding sources: NIST (64%), Other Government Agencies (32%), Other (4%)

Objective: Develop measurement methods and standards for characterizing laser sources and detectors used primarily with steady-state radiation. Develop and maintain measurement services for laser power & energy, optical fiber power, and related parameters (e.g., spectral responsivity, linearity, etc.)

Background: The development of lasers in the 1960s opened the door to new technologies and industries that could make use of the peculiar properties of laser radiation (i.e., spatial coherence, temporal coherence, narrow line width, high irradiance levels, etc.). The implementation of laser sources into industrial systems as well as research laboratories has been historically limited or enhanced by the ability to accurately characterize the emitted radiation. Consequently, NIST has been developing and providing measurement services to the laser community since the late 1960s. As new wavelengths and laser types have emerged, NIST has developed the appropriate new detector standards and measurement techniques to support this growth. Optical power detectors continue to be the most common piece of test equipment for supporting optical fiber telecommunication systems and as the technology evolves, higher accuracy power measurements have become crucial. In addition to higher accuracy, calibration customers have requested that we improve our capability to measure other detector properties such as linearity and spectral responsivity. Medical uses of lasers are continuing to evolve, with refractive eye surgery being a recent example where total beam energy and spatial beam quality are critical measurement requirements. Quantitative knowledge about the irradiance profile and propagation characteristics of laser beams is essential to understanding the properties of emerging new technologies such as vertical cavity surface emitting lasers (VCSELs). Beam profile standards are becoming increasingly important for analyzing the radiation propagating through optical systems containing many optical components (e.g., lenses, fibers, filters, etc.). Important industrial applications of beam profile standards include optical data storage, high resolution printing, and semiconductor photolithography.

Current Tasks:

1. Develop spectral responsivity measurement capability for optical power detectors

FY 1993	Project initiated to develop spectral responsivity capability for optical power meters.
FY 1994	Prototype system developed and used for special test measurements at uncertainties of ±2%.

FY 1995	Improved system designed, equipment procured, and system established.
FY 1996	Began assessment and improved measurement uncertainty; Performed special test measurements for customers.
FY 1997	Complete uncertainty improvement and analysis; automate measurement system, train technicians, and implement fully documented measurement services.
FY 1998	Continue improvement of measurement uncertainties, and provide calibration services to customers; Provide specialized tests to industrial and research communities as required.

2. Develop and provide measurement services for optical fiber power meters

FY 1987	Received numerous requests for optical fiber power measurements.
FY 1988	Developed parallel beam measurement capability for power measurements of laser beams operating at a wavelength of 850 nanometers and began offering measurement services at 100 microwatt power level.
FY 1989	Developed parallel beam measurement capability for wavelengths of 1300 and 1550 nanometers and offered associated measurement services at 100 microwatt power level.
FY 1990	Received requests for measurements using various types of connectors as requests for parallel beam measurement declined.
FY 1991	Developed automated measurement capability for connectorized fiber delivery to power meters at 100 microwatt power levels.
FY 1992	Added 670 nanometers and 780 nanometers to wavelength capability.
FY 1994	Compared various methods of measuring detector linearity and selected optimum method for optical fiber power meters.
FY 1995	Developed linearity measurement system for detectors of laser radiation at wavelengths of 1300 and 1550 nanometers and use for Special Test measurements over wide range (60 dB) of power.
FY 1996	Developed linearity measurement capability for 850 nanometers; Developed tunable laser system for optical fiber power meter measurements.
FY 1997	Improve linearity and tunable laser measurement system to provide enhanced measurement support; Perform study of connector effects on measurements; obtain formal approval for optical fiber power measurement services.
FY 1998	Continue improvement of measurement uncertainties; Develop improved transfer standards traceable to the high accuracy cryogenic radiometer; Provide measurement services to industry.

3. Develop and provide measurement services for laser power & energy detectors

FY 1967-93	Developed and provided power measurement services at various wavelengths at powers up to 300 watts.
FY 1994	Based on requests from material processing industry, procured high power lasers and began development of high power calibration capability for lasers operating at a wavelength of 10.6 micrometers.
FY 1995	Provided calibrations for laser output power up to power levels of 1 kilowatt and a wavelength of 10.6 micrometers; Developed fiber delivery system for high power (500 watts) 1.06 micrometer measurements; Initiated high laser round robin.
FY 1996	Implemented high power 1.06 micrometer calibration measurements; Continued high power round robin.

FY 1997	Complete high power round robin; Modify high energy laser calorimeter; Investigate discrepancy with PTB.
FY 1998	Develop improved transfer standards for high power laser measurements; Provide high quality measurement services to industry.

4. Improve accuracy of laser and optical fiber power measurements

FY 1994	A survey of standards laboratories and customer input specified need for improved accuracy for laser and optical power measurements at NIST
FY 1995	Developed plan for obtaining improved primary standard and secondary standard; procurement of cryogenic radiometer initiated.
FY 1996	Installed and tested cryogenic radiometer; Built and tested automated measurement system.
FY 1997	Develop prototype secondary standards (diode trap and pyroelectric trap designs); using new primary and secondary standards, fully implement high accuracy measurement chain.
FY 1998	Develop improved cryogenic radiometer designs with faster response time and improved dynamic range; Provide measurements to support laser and fiber optic power calibration services.

5. Develop beam profile measurement capability

FY 1993	Requested by industry to become involved in development of beam profile standards and measurements to support industry.
FY 1994	Participated with U.S. industry to help develop an international voluntary beam profile standard document; Performed beam width round robin with industry.
FY 1995	Developed state-of-the-art beam profile measurement system; Initiated second beam width and divergence round robin.
FY 1996	Improved beam profile measurement systems; Investigated sources for use in a round robin.
FY 1997	Continue development of standards for beam profile measurements; Develop beam profile measurement capabilities for excimer lasers used in photorefractive eye surgery; Investigate methods for profile measurements of tightly focused beams used in optical data storage.
FY 1998	Use new beam profile standards in round-robin with industry; Investigate standards appropriate for medical applications of excimer lasers; Develop beam profile measurement capability for pulsed lasers.

6. Develop deep ultraviolet (DUV) calorimeters for excimer laser measurement capability.
(Early work previously included in High Speed Source and Detector Measurements Project.)

FY 1990	Requested by industry to build capability for 248 nanometer excimer laser calibrations.
FY 1991	With funding from SEMATECH, built and delivered to GCA two DUV calorimeters for laser energy measurements.
FY 1994	Received calorimeters from GCA and established measurement service for excimer laser energy meter calibrations at 248 nanometers.
FY 1995	Performed numerous calibrations of excimer laser power and energy meters at 248 nanometers.

FY 1996	Again requested by industry to expand capabilities for excimer laser measurements to 193 nanometers; Began search for candidate calorimeter volume absorbing materials a 193 nanometers; Participated in collaboration between NIST, Massachusetts Institute of Technology/Lincoln Laboratories, and SEMATECH on DUV photolithography issues.
FY 1997	Continue investigations of volume absorbing materials for use in extending existing DUV calorimeter design for measurements at 193 nanometers; Build new DUV calorimeters for 193 nanometers; Install new excimer laser on loan from SEMATECH.
FY 1998	Provide calibration services at 193 nanometers for excimer laser power and energy meters; Develop improved excimer laser calorimeter designs with higher accuracy, better long-term stability, and wider spectral coverage.